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14. ABSTRACT

This project addresses two challenges in complex human-machine systems: i) predicting system responses that emerge from the combined actions of multiple networked agents and ii) designing components to establish desirable system operations from collective agent behaviors. In complex human machine systems, the “agents” are comprised of both programmable components and human decision makers. An ultimate objective is to enable effectively controlled coordination of this combination through the development of computational algorithms and human incentives supported by analysis, simulation, fielded surveys, and operational performance feedback. Work has continued on two complementary directions towards our objective. First is the analysis and simulation of agent coordination. Second is understanding the emergence of patterns and interactions among organizational cultural norms, through the use of fielded surveys and operational performance feedback, specifically in the area of organizational safety for high-risk, high-consequence systems.

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Abstract: This project addresses two challenges in complex human-machine systems: i) predicting system responses that emerge from the combined actions of multiple networked agents and ii) designing components to establish desirable system operations from collective agent behaviors. In complex human machine systems, the "agents" are comprised of both programmable components and human decision makers. An ultimate objective is to enable effectively controlled coordination of this combination through the development of computational algorithms and human incentives supported by analysis, simulation, fielded surveys, and operational performance feedback. Work has continued on two complementary directions towards our objective. First is the analysis and simulation of agent coordination. Second is understanding the emergence of patterns and interactions among organizational cultural norms, through the use of fielded surveys and operational performance feedback, specifically in the area of organizational safety for high-risk, high-consequence systems.

Summary of Accomplishments

Our work has focused on three complementary directions towards our objective. First is modeling, analysis and simulation of agent coordination. Second is understanding the emergence of patterns and interactions among organizational cultural norms, through the use of fielded surveys and operational performance feedback, specifically in the area of organizational safety for high-risk, high-consequence systems. Third is exploring how this empirical data exemplifies and challenge the principles developed in modeling, analysis and simulation work.

Multiagent coordination: Distributed multiagent systems consist of a collection of decision making components with limited processing capabilities, locally sensed information, and limited inter-component communications, seeking to achieve interdependent (and sometimes global) objectives. This requires coordination. The distributed nature of information processing, sensing, and actuation makes these systems a significant departure from traditional centralized decision architectures and more aligned with the frameworks of game theory (i.e., the study of interactions between decision makers) and information dynamics (i.e., the study of flow and differential interpretation of information in populations). Of particular relevance are:

- Game theoretic learning, in which the focus shifts away from equilibrium solution concepts and towards the dynamics of how decision makers reach equilibrium. Recent work explores the role of game theoretic learning as an approach to design online learning algorithms for multiagent coordination.
- Distributed optimal agreement, which builds a general model of stochastic agreement dynamics in large, structured decision spaces, under limited information and structured interaction regimes.

Specific work done in these areas includes:

- *Cooperative control & potential games:* Recent years have seen significant interest in multiagent coordination from the viewpoint of "cooperative control". Typical work in this year derives steering algorithms for coordination of motion of mobile vehicles and sensors. Our recent work establishes the strong connection between cooperative control and game theoretic learning, specifically for so-called "potential" and "weakly acyclic" games. Indeed, several cooperative control problems such as consensus and dynamic sensor coverage can be formulated in these settings. Motivated by this connection, we build upon game theoretic concepts to better accommodate a broader class of cooperative control problems. In particular, we extend existing learning algorithms to accommodate (i) restricted action sets caused by limitations in agent capabilities and (ii) group based decision making. Furthermore, we also introduce a new class of games, called sometimes weakly acyclic games, for time-varying objective functions and action sets, and provide distributed algorithms for convergence to an equilibrium.
- *Log-linear learning:* Log-linear learning is a specific algorithm for multiagent coordination motivated by statistical physics. In log-linear learning, agents use stochastic decision rules in which are myopically optimal with high probability while exploring suboptimal possibilities with low probability. The traditional analysis of log-linear learning has centered around explicitly computing probabilities of the collective actions of agents. This analysis relied on a highly structured setting: i) players' utility functions constitute an exact potential game, ii) players update their strategies one at a time, which we refer to as asynchrony, iii) at any stage, a player can select any action in the action set, which we refer to as completeness, and iv) each player is endowed with the ability to assess the utility he would have received for any alternative action provided that the actions of all other players remain fixed.

Since the appeal of log-linear learning is not solely the explicit form of the stationary distribution, we seek to address to what degree one can relax the structural assumptions while maintaining that only potential function maximizers are the stochastically stable action profiles. In this work, we introduce slight variants of log-linear learning to include both synchronous updates and incomplete action sets. In both settings, we prove that only potential function maximizers are stochastically stable. Furthermore, we introduce a "payoff-based" version of log-linear learning, in which players are only aware of the utility they received and the action that they played. In payoff-based log-linear learning, we also prove that only potential maximizers are stochastically stable. The key enabler for these results is to employ methods of "stochastic stability".

- *Efficient network formation:* This work considered the coordination problem of network formation, where agents can form and sever unidirectional links and derive direct and indirect benefits from these links. We formulate and analyze an evolutionary model in which each agents choices depend on its own previous links and benefits, and link selections are subject to random perturbations. Agents reinforce the establishment of a link if it was beneficial in the past, and suppress it otherwise. We illustrate the flexibility of the model to incorporate various design criteria, including dynamic cost functions that reflect link establishment and maintenance, and distance-dependent benefit functions.We show that the evolutionary process assigns positive probability to the emergence of multiple stable configurations (i.e., strict Nash networks), which need not emerge under alternative processes such as best-reply dynamics. We analyze the specific case of so-called frictionless benefit flow, and show that a single agent can reinforce the emergence of an efficient network through an enhanced evolutionary process known as dynamic reinforcement.

- *Self assembly:* Self assembly is a particular kind of multiagent coordination problem in which the "agents" are individual components/pieces (e.g., atoms) of a complete assembly (e.g., molecule) and are severely constrained in terms of their communication and processing capabilities. This work presents methods for distributed self-assembly that utilize simple rule of thumb control and communication schemes providing probabilistic performance guarantees. This approach represents a staunch departure from existing approaches that require more sophisticated control and communication, but provide deterministic guarantees. In particular, we show that even under severe communication restrictions, any assembly described by an acyclic weighted graph can be assembled with agent memory and computation complexities that are linear in the number of nodes contained in the desired assembly graph. We introduce the concept of stochastic stability to the self-assembly problem and show that stochastic stability of desirable configurations can be exploited to provide probabilistic performance guarantees for the process. Relaxation of the communication restrictions allows simple approaches giving deterministic guarantees. We establish a clear relationship between availability of communication and convergence properties. Self-assembly tasks are considered for the cases of many and few agents as well as large and small assembly goals. Sensitivity of the presented process to communication errors as well as ill-intentioned agents is considered.

- *Agreement Dynamics:* Agreement is a fundamental class of coordination problems that appears ubiquitously in distributed systems. Using a mix of simulation studies and analytical modes we study three issues: which critical factors impact the ability to reach consensus in a distributed population; how do those factors influence the type or quality of solutions reached; and how do those factors impact convergence time? We largely study these issues in the domain of evolving communication and cultural regimes for multi-agent systems. Our basic findings are that a) key factors include *agreement space size*, *agreement space structure*, and *network-biased information propagation*; b) network topologies influence convergence time and quality by structuring information propagation, and c) some network structures yield performance characteristics with such high *variance* (over multiple runs) as to be

effectively unpredictable in time or quality; networks are sometimes uncertainty multipliers.

- *Information Theory of Networks:* This work studies the relationship between network structure/topology and the ability to accumulate information. We have developed the basics of an information theoretic model that can help explain why certain information dynamics processes (say, consensus/agreement processes, opinion dynamics models like Voter models, load-balancing protocols, or innovation-diffusion) occur differently under different network topologies. Briefly, local estimates of global states are critical for coherent consensus decisionmaking—for example when agents are trying to reach agreement on some information state or some collective action plan, by locally converging to it. Incomplete networks limit propagation of global information to incomplete samples at any step, (e.g., an agent only gets information from its network neighbors, not from all other agents, hence it collects only samples of the global state). If these samples inaccurately reflect global statistics, (e.g., violate mean-field assumptions) then local decisions can be globally incoherent. Network topology is thus a sampling structure, and agents must trade off time (multi-step flows of information) for accuracy when making local estimates of global states in a networked information flow. In terms of dynamics, network states that are changing faster than information can propagate these estimates will be outdated and decisions will be bad.

- *Distributed constraint agreement (DCA).* Individual cognitive states may be complex systems of constraints that need solving dynamically as situations evolve. If such "internal" constraint networks are underconstrained, many potential solutions exist per agent. In many agreement and coordination problems (e.g., agreeing on common communication protocols using complex languages) *populations* of agents must align their individual constraint solutions, using completely decentralized, and sometimes limited, information. We have developed algorithms for DCA and demonstrated them on the problems of "vowel shifting." Our approach explains how dynamic vowel systems can maintain internal consistency (e.g., ability to accurately differentiate vowel sounds in real time, which depends on individual inter-vowel constraints) and population-wide coherence in practical time.

Mechanism design: The prior discussion on multiagent coordination deals with agents that are programmable components. As the terminology implies, complex human-machine systems involve human decision makers who cannot be "programmed" to execute a desired algorithm. Rather, one must develop rules that incentivize rational decision makers to taking desirable actions that contribute to collective performance, which need not be exactly aligned with individual welfare. This concern has been investigated in the economics literature under the framework of "mechanism design". A "mechanism" is a policy that maps distributed agent messages to centralized policy decisions. Mechanism design seeks to derive rules that incentivize distributed agents to report "truthful" messages, and consequentially result in effective policy decisions.

Our work in mechanism design explored two directions motivated by feedback control considerations, namely, model uncertainty and dynamics.

- *Robust mechanism design:* The traditional setup for mechanism design admits uncertainty in the models of agents. However, this uncertainty must conform to a specific and restrictive structure. An typical example is in auctions, where agent valuations of an auctioned item are unknown, but assumed to conform to a specified and known probability distribution. We show optimal auctions are "fragile" in the following sense. The slightest deviation from the assumed probability distribution can result in agents not participating in the auction. In other words, auctions efficiency is discontinuous with respect to the assumed setup. We are currently exploring methods to derive alternative "robust" auctions that trade-off idealized efficiency with robustness.

- *Dynamic mechanism design:* Traditional mechanism design deals with a "one shot" setup, i.e., the mechanism is executed only once. An emerging topic is so-called "dynamic" mechanism design, in which the mechanism is implemented as part of an ongoing dynamic process. An example is a continuing flow of agents that bid to utilize limited resources. The mechanism seeks to accommodate current agents while hedging for the presence or absence of future agents. The resulting mechanism then takes the form of a feedback control policy. This work is exploring the use of feedback control methods, such as dissipation inequalities, to construct effective dynamic mechanisms.

- *Workload model optimization:* Despite the existence of several automated air traffic conflict resolution algorithms, there is a need for formulations that account for air traffic controller workload. This work presents such an algorithm with controller workload constraints modeled parametrically. To this end, we first develop an integer programming model for general conflict resolution, which emphasizes the minimization of fuel costs, and runs in near real-time. A parametric procedure based on this model is then developed to consider controller workload limitations. Two versions of the parametric approach are described, along with computational results. It is demonstrated that both formulations can be used to capture a broad range of possible controller actions.

Simulation testbed for general information dynamics problems: We have constructed a modular Java-based simulation system for modeling general information dynamics problems. The testbed includes modeling facilities for agents with their cognitive architectures and encode knowledge; three types of networks including geographic networks (physical layout relations), communication networks (information flows, messages), and social networks (ties, affiliations, kinship); Worlds populated with objects, and sensors/effectors for agents; Measurement and experimentation facilities. This testbed is running in prototype form and is being used in many experiments underpinning the research above.

Simulation model of information dynamics in safety-critical systems. We studied the effects of information flow and interpretation (mediated by networks, culture, etc.) on levels of safety in safety-critical high-confidence systems. We have a preliminary model of how information flow affects safety at population levels. We have explored mechanism design for safety critical organizational processes based on agents adaptively learning to propagate information to the right consumers, and collectively developing robust common interpretive frames for message content over time.

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